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Title: Report on Task USA A 0931 (A.252) Implementation of Fast, Front-End Electronics for Improved Low-Dead Time Neutron Counting

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Report on Task USA A 0931 (A.252)
Implementation of Fast, Front-End Electronics for Improved Low-Dead Time Neutron Counting

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Content:

1. Background

The International Atomic Energy Agency's (IAEA) Department of Safeguards is working on the elaboration and implementation of advanced Non-Destructive Assay (NDA) methods, generally known as neutron noise analysis, for the verification of critical and sub-critical cores containing substantial quantities of direct use nuclear material.

These verification methods rely on interpreting time properties of the neutron multiplication process, which are to be extracted from measured neutron pulse trains. The interpretations are highly dependent on the quality of the measured data, which is directly related to the capability of an employed neutron detector to resolve very close detection events originating from neutron bursts produced in a highly multiplying medium. Therefore, the application of detectors with minimum dead-time, pile-up, and other distortion effects is required.

This report describes the work under Task USA A 0931 (A.252 Implementation of fast, front-end electronics for improved low-dead time neutron counting) The specific tasks of the project are:

- Fabrication of KM200 electronics in a standalone package suitable for implementing in real criticality measurements.
- Optimize KM-200 setting for specific detector
- KM200-STANDALNOE and PDT comparison test
- Wrap-up the report and ship the detectors with electronics back to IAEA.
- Prepare training presentation and conduct hands-on training session for IAEA staff

2. KM200-STANDALONE Electronics Technical Description

The KM200-STANDALONE devices implement the KM-200 electronics' functionality and performance described in [1].

2.1. Mechanical Description

The compact KM200-STANDALONE package consists of the following components (as shown on figure 1):

- An HN connector that connects with the detector.
- A body that with dimensions of 1.2"X1.2"X3".
- Interface cables coming out of the back of the device opposite to the HN connector.

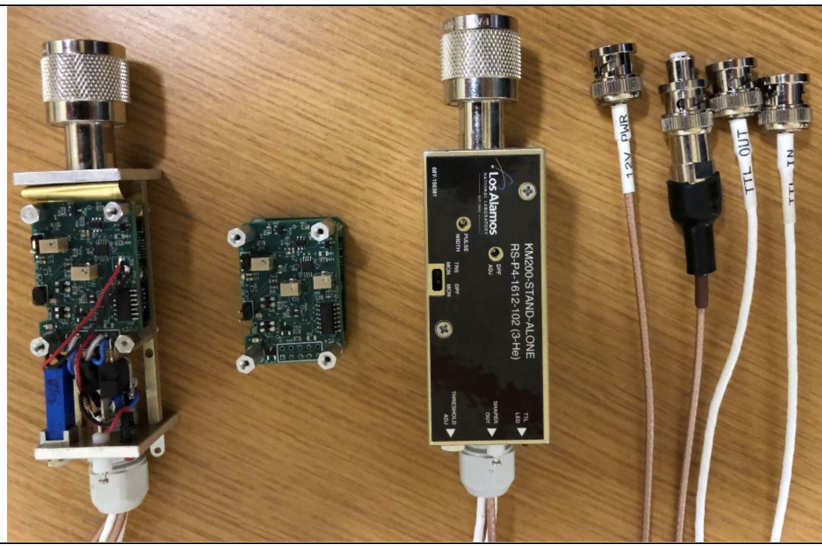


Figure 1. View of KM200-STANDALONE and the electronics contained in it.

On the side of the detector there are several openings for access to two potentiometers that control the pulse width of the logic output and the double pulsing filter. On the same side there also an opening for access of two test points for monitoring the threshold value and double pulsing filter value. These are labelled as PULSE WIDTH, DPF ADJ TRS MON, and DPF MON respectively.

The back side of the detector (where the interface cables emerge from) has the threshold adjustment potentiometer, a test point for the analog shaper pulse output, and an LED that flashes when a pulse is detected. These are labelled as THRESHOLD ADJ, SHAPER OUT, and TTL LED respectively. The label on the side of the KM200-STANDALONE package has information about the type of detector the unit had been optimized for.

2.2. Inputs and Outputs

There is a female HN connector in the front of the KM200 package that mates with the HN connector of the corresponding detector (3-He, B10, Fission Chamber).

There are four coaxial cables coming out of the back of the package. They are as follows:

- BNC terminated cable labelled TTL IN. This is a logic input that allows daisy-chaining of multiple devices. It can receive the output from a preceding KM200 and pass it on to the next.

- BNC terminated cable labelled TTL OUT. This is the logic output that produces a pulse for each detected event and passes through any pulses received at TTL IN.
- SHV terminated unlabelled cable. This is the high voltage bias input intended to bias the detector.
- BNC terminated cable labelled 12V PWR. This is the power supply input nominally receiving 12V. The input voltage can be from 6.5V to 16V.

2.3. Controls, Monitoring Points, and Indicators

Detection threshold: The threshold is controlled by a potentiometer located in the back of the package labelled as THRESHOLD ADJ. The potentiometer can be turned with a small flat screwdriver. Turning the potentiometer clockwise lowers the discriminator voltage (makes the discriminator more sensitive). A voltage value related to the discriminator threshold setting can be monitored by measuring the voltage at the test point labelled TRS MON.

Double pulsing filter (DPF): A rejection filter for double pulsing that is controlled by a potentiometer labelled as DPF ADJ. Turning the potentiometer counter clockwise decreases the double pulsing filter strength. A voltage value related to the strength of the DPF can be monitored by measuring the voltage at the test point labelled as DPF MON. Refer to the Setup procedure section for information about setting the threshold and DPF.

An analog signal from the last stage of the shaper is available at the test point labelled SHAPER OUT.

The LED labelled TTL LED blinks red every time a pulse is detected. At high count rates it may appear to be constantly turned on.

2.4. Experimental Setup

Figure 2A shows a sketch of the measurement setup used in the evaluation of the amplifiers' performance. Figure 2B shows and example measurement with PDT10A and detector number RS-P4-1612-102.

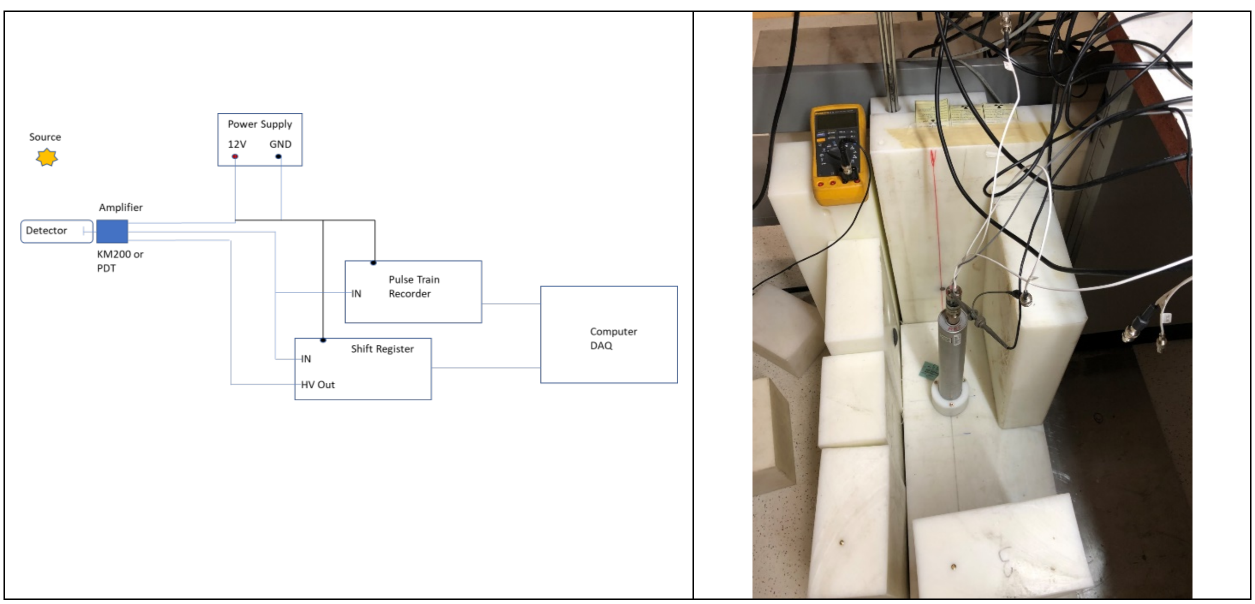


Figure 2A. Sketch of the experimental setup.	Figure 2B. Measurement with 2” 3-Helium detector.

2.5. Signal Processing and Optimization

Optimization of an amplifier's time constants for a specific detector results in optimal dead performance, no double pulsing, and gamma sensitivity benefits. This optimization is complicated by the significant variation of charge collection times and pulse shapes from pulse to pulse in the same detector. The shaping time has to be optimized separately for each detector type because the maximum charge collection times depend on detector specific parameters like gas mixture, pressure, and detector geometry. A discussion of properties in proportional counters, signal processing and methods for improvement can be found in [1,2] and recently issued patent [3]. As part of the optimization procedure we have estimated the charge collection time of the IAEA 3-He tubes using a charge sensitive amplifiers with compensation of the ionic component (part of LANL zero DT setup). The output from these amplifiers shown on the oscilloscope snapshots of Figure 3 demonstrate the dramatic difference in detector charge collection times in the two 3-He detector types provided by the IAEA. Figure 3 also illustrates the wide variance of pulse shapes and rise times within the same detector.

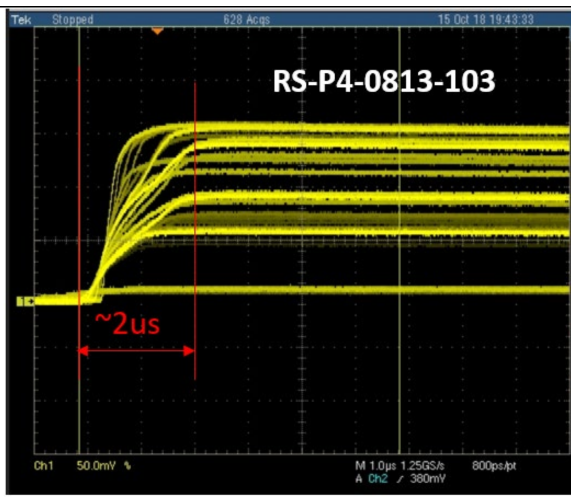
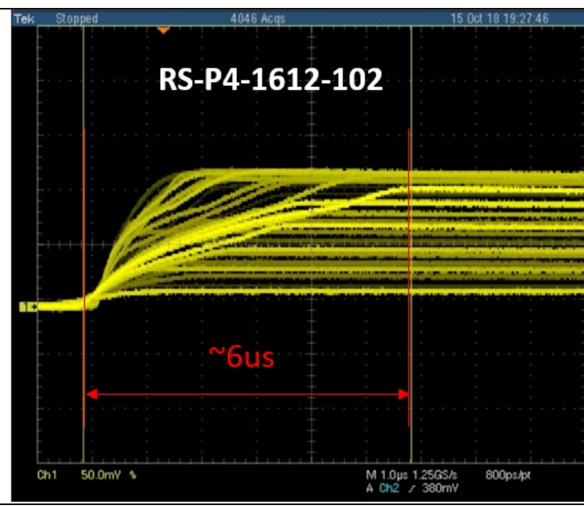
	

Figure 3A. Charge pulse response of a standard 3-He tube. The charge collection time for its slow pulses is around 2us. Some pulses are much faster.	Figure 3B. Charge pulse response of a slow 2” 3-He tube. The charge collection time for its slow pulses is around 6us. Some pulses are much faster.

To select the optimal time constants for the IAEA 3-He detectors we used the charge the charge sensitive amplifier results as a starting point and continued to iterate using high voltage plateau and time interval measurements.

For the B10 and fission chamber detectors the initial time constant determination was done using manufacturer data and indirect measurements.

3. KM200- STANDALONE Setup Procedure

3.1. **Introduction.**

The setup of typical He-3 electronics like A-111, PDT-10A, PDT-110A, etc. is based on adjustment of amplifier sensitivity (A-111 and PD-10A, PDT-11A have gain adjustment, KM200 has discriminator threshold adjustment). These are used to set the beginning of the plateau (the knee) at a desired HV bias voltage. There are two steps for making a set of electronics operate at the same desired bias voltage: a) initial setting of a single amplifier sensitivity, and b) gain (sensitivity) matching of the rest of amplifiers in the neutron counting system.

Because the A-111 and other commercial amplifiers, have a sensitivity adjustment control potentiometer but not an indication for its settings, the gain matching step is usually done by using radioactive source and iterative procedure for matching the slope of plateaus on every amplifier. The gain matching using radioactive source is tedious and time consuming lab procedure. Troubleshooting and replacement of defective amplifier in the field is even more challenging.

KM200 can be adjusted using the same procedure as commercial amps, but it also offers options for less time-consuming gain matching because it has a test point with a DC voltage proportional to the set threshold. This voltage can be replicated on devices that are to be gain-matched, thus avoiding the need to take plateaus.

Step 1: The first step in sensitivity adjustment (which is the same for KM200 and for the other common ^{3}He amplifiers) is to iteratively take several high voltage plateaus with different amplifier gain/sensitivity settings until the desired high voltage operating point is achieved (i.e. 1680V is 40 volts above the plateau knee).

KM200 allows the user to apply a double pulsing filter (DPF) if the plateaus taken in the sensitivity adjustment step are degraded due to double pulsing. This degradation is often expressed by an excessive slope at the plateau. The DPF adjustment procedure and plots of the DPF's effect on plateaus can be found in section 3.4.

Step 2: Gain matching, is a particularly tedious operation for multi-detector systems. It involves matching the plateau characteristics of all the amplifiers to the one that was adjusted in step one. KM200 offers a very quick way to do this using a digital multi meter (DMM) to measure a monitoring pin voltage output that is proportional to the threshold setting. This gain matching procedure is described in section 3.2.

Alternatively, a LANL designed hand held charge calibrator can be used for extracting the sensitivity setting of the amplifier adjusted in step one and replicating it in the rest of the amplifiers in the system regardless if they are KM200 or other common ^{3}He amplifiers. This procedure is described in section 2.3. Note that the sensitivity matching with the charge calibrator is reliable only if it's done across the same type and model of electronics, i.e. you can't match the neutron pulse sensitivity of a KM200 and a A111 using the charge calibrator.

3.2. **Threshold adjustment and gain matching using KM200 monitor pins and DMM**.

Figure 4 shows the setup for threshold adjustment and subsequent gain matching of KM200-STANDALONE amplifiers. Follow the next steps to perfume this procedure:

- Choose one channel/amplifier to perform "step 1" described in the introduction.
- Disable the DPF by turning the potentiometer marked as DPF ADJ counterclockwise by 10 turns.
- Perform "step 1" (section 3.1) on the chosen channel (iteratively find the desired plateau position) by adjusting the threshold using potentiometer marked as THRESHOLD ADJ.
- If the plateau slope is more than 2%/100V perform DPF adjustment using potentiometer marked as DPF ADJ as described in section 3.4 on the selected channel.
- Once the plateau position and slope are as desired, use DMM to measure the voltages between ground and the monitoring test points TRS MON and DPF MON. Record these voltages for use in the gain matching step of this procedure.
- For each of the remaining amplifiers, replicate the threshold setting by connecting the DMM between ground and the TRS MON monitoring pin and turning potentiometer THRESHOLD ADJ until the voltage reading is within 5% of the recorder value.
- For each of the remaining amplifiers, replicate the DPF setting by connecting the DMM between ground and the DPF MON monitoring pin and turning potentiometer DPF ADJ until the voltage reading is within 5% of the recorder value.

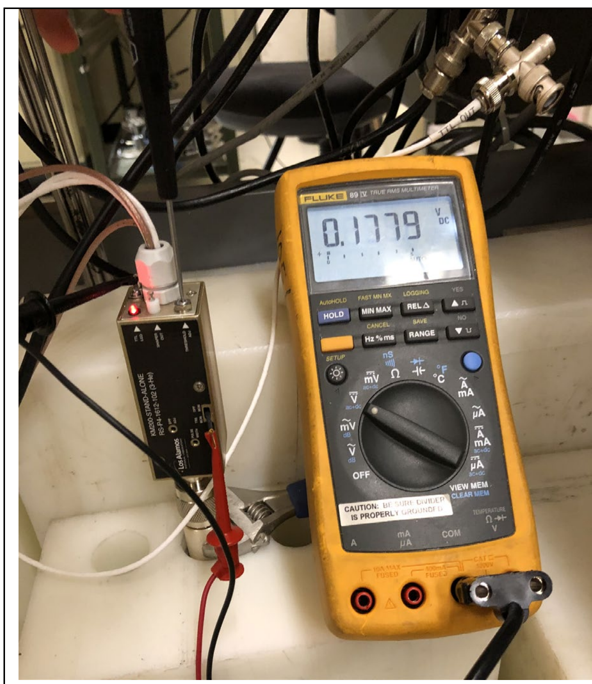


Figure 4A. Threshold adjustment and sensitivity/gain matching setup for KM200-STANDALONE.

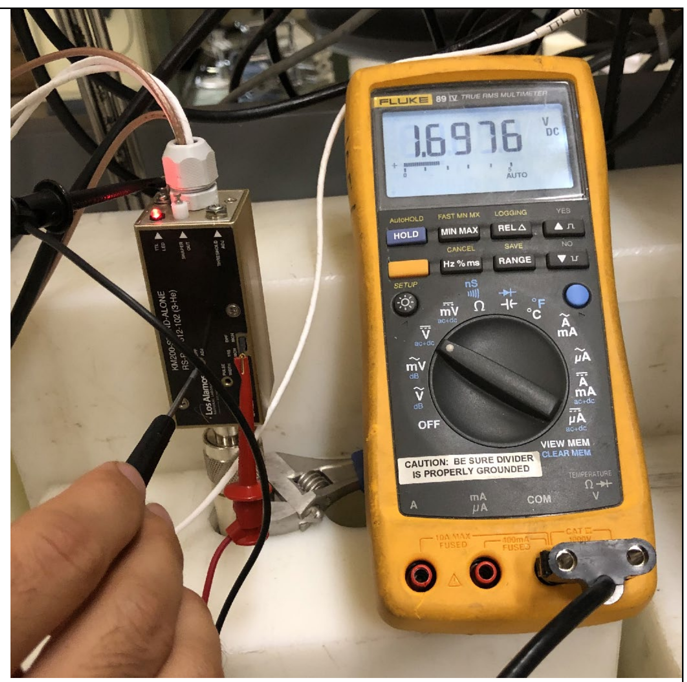


Figure 4A. Double Pulsing Filter (DPF) adjustment and DPF matching setup for KM200-STANDALONE.

3.3. Threshold setup and gain adjustment using LANL Universal Charge Calibrator.

The Universal Charge Calibrator (figure 5) offers a capability for fast precise setting of sensitivity of an amplifier (shaper and discriminator) to a charge signal injected in the input. It is applicable for gain matching for KM200 as well as other commercial amplifiers such as A-111 or PDT-10. Detailed principle of operation summary and viewgraphs of the charge calibrator are shown in Appendix 1. An example setup is shown on figure 5, where the charge calibrator is used with a KM200-STANDALONE device and with an A111 JAB board.

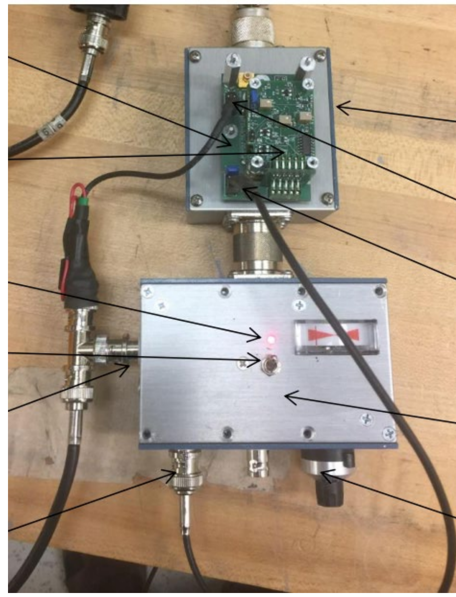
3.3.1 Initial adjustment and sensitivity sampling (refer to Fig.4 and Appendix 1):

- Choose one amplifier and one ^{3}He detector from the set of amplifiers that need to be calibrated.
- Perform "step 1" described in the introduction (section 3.1) on the chosen amplifier using the chosen detector (i.e. adjust the sensitivity until the high voltage plateau is at the desirable position).
- Sample the adjusted sensitivity of the calibrated amplifier by performing the following steps:
  - Connect the input of the amplifier with previously adjusted sensitivity to the charge calibrator charge output (the charge injection head). Figure 5 shows the connection for KM200 and an A111 based amplifier. The charge calibrator allows PDTs to be connected too.
  - Connect power to the amplifier.
  - Connect the counting output signal of the amplifier to the charge calibrator input called TTL IN.
  - Turn ON the amplifier and charge calibrator power
  - Observe the Zero Indicator on the charge calibrator (the needle indicator with center equilibrium position).
  - If the zero indicator needle is to the left of center, turn the injector potentiometer **clockwise (CW)** to set the dial in the middle of the scale.
  - If the zero indicator needle is to the right of center, turn the injector potentiometer **counterclockwise (CCW)** to set the dial in the middle of the scale
  - When the zero indicator needle is positioned in the middle, the charge calibrator is set to inject the same amount of charge as the sensitivity threshold of the calibrated amplifier. This setting can be used to adjust the remaining amplifiers.
  - Secure the charge calibrator's setting by locking the injector potentiometer.

3.3.2 Procedure for threshold setting (gain matching) of the remaining amplifiers. This procedure is intended to set the thresholds of all amplifiers to the same value as the one calibrated in section 3.3.1:

- Connect the input of the next amplifier that is to be gain matched to the charge calibrator charge output (the charge injection head).
- Connect power to the amplifier.
- Connect the counting output signal (TTL OUT) of the amplifier to the charge calibrator input called TTL IN.
- Turn ON the amplifier and charge calibrator power
- Observe the Zero Indicator on the charge calibrator (the needle indicator with center equilibrium position).

- Turn the threshold or gain adjustment potentiometer *on the amplifier* until the charge calibrator zero indicating needle is position in the middle. The specific direction of potentiometer rotation depends on the type of amplifier, therefore the user has to try both CW and CCW.
- When the amplifier threshold is adjusted so that the needle on the zero indicator is in the middle, the gain/threshold of the amplifier is matched to the gain/threshold of the calibrated amplifier
- Repeat the steps in 3.3.2 for all amplifiers that have to be gain matched.

	
Figure 5A. KM200- STANDALONE connected to the LANL Universal Charge Calibrator.	Figure 5A. A111 JAB board connected to the LANL Universal Charge Calibrator.

3.4. Double Pulse Filter Setting

The effect of the KM200's Double Pulsing Filter (DPF) on the counting characteristics of the amplifier is explained in [1]. The DPF adjustment is based on taking of multiple plateaus at different setting of DPF potentiometer marked as DPF ADJ. The DPF rejects the parasitic double pulsing events. These events cause excessive slope in high voltage counting characteristic that obscures the normally flat high voltage plateau. Applying DPF can flatten the plateau; however, excessive DPF can shift he knee of the high voltage characteristic to the right (see figure 6). DPF shouldn't be increased if the knee is beginning to be affected.

3.4.1 Measurement setup (refer to Fig.6).

- Measurement equipment:
  - The KM200 amplifier that will be adjusted

- Digital Multi Meter (DMM).
- Pulse Train Recorder like PTR-32.
- Less than 1mm wide flat screw driver.

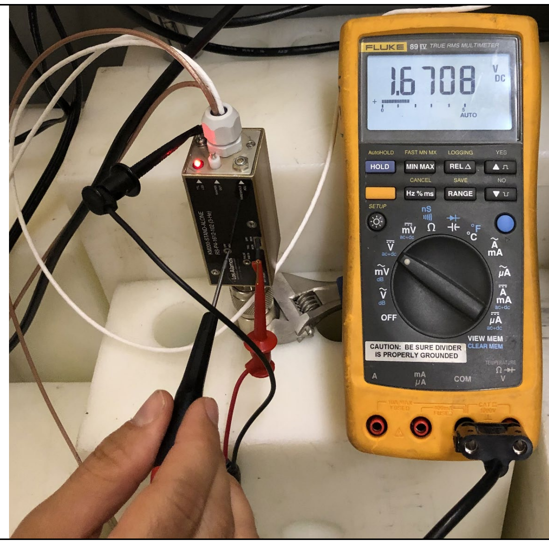


Fig.6 Setup for Double Pause rejection adjustment. The ground lead (black) of DMM is connected to a grounded solder lug. The signal lead (red) of DMM is connected to DPF MON test point.

- Set amplifier threshold as described in section 3.2
- Turn potentiometer DPF ADJ counterclockwise 10 full revolutions. This will set the DPF filter to its lowest value. When the DMM is connected between test point DPF MON and ground, it should read around 4.5V. This corresponds to disabled DPF.
- Build a family of plateaus like the one shown on figure 7 by changing the DPF settings (through potentiometer DPF ADJ) from 4.5V (disabled DPF) to about 1.5V (Strongest DPF) on DPF MON.
- From the curves select DPF value that provide flattest region without affecting the knee of the plateau.
- Select a desired HV set point on the plateau and take Time Interval Histogram (TIH) data using a list mode pulse recorder like PTR32 to verify the level of double pulsing. Figure 8A shows a TIH with insufficient DPF, and figure 8B shows the TIH after the DPF was optimized.
- It is possible that the amplifier shaper is too fast for the 3-He detector under test, and the DPF cannot eliminate all double pulsing. In that case a slower shaper has to be used with this detector.

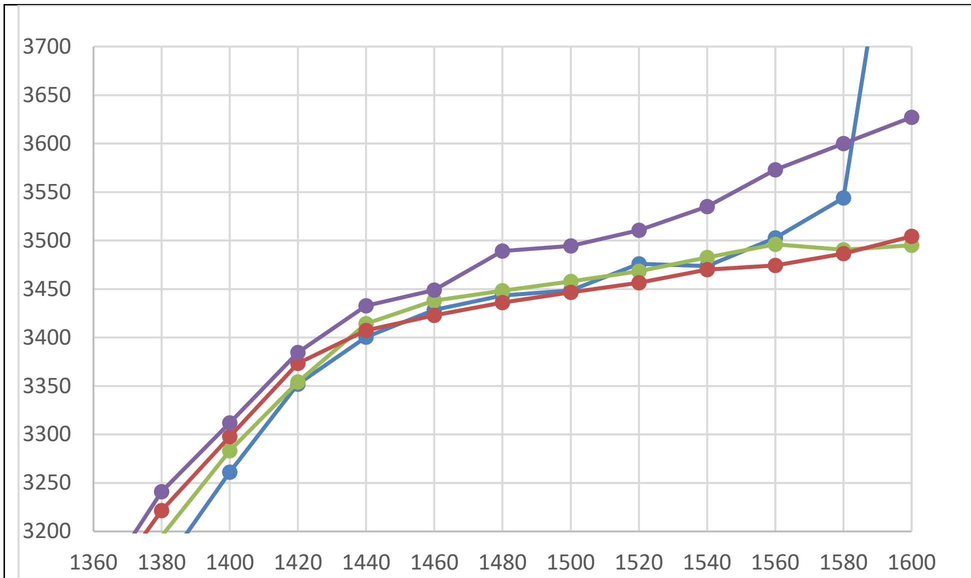


Figure 7. KM200 Plateaus with 200 mV threshold settings taken at different values of DPF. The DPF=1.6V provides flat region (the plot in red color). The purple plateau shows increased slope due to double pulsing. The green shows a decrease in sensitivity resulting in shift of the plateau knee.

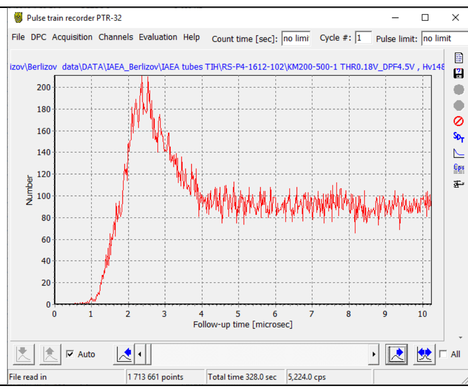


Figure 8A. TIH of KM200 with minium DPF setting.

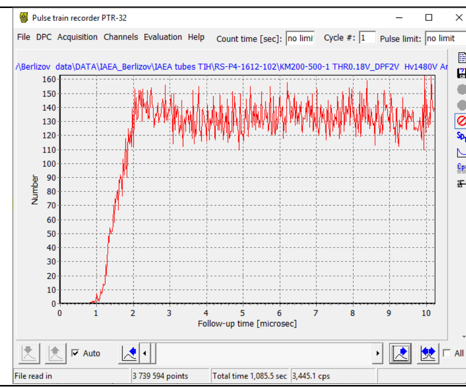


Figure 8B. TIH of KM200 with optimized DPF setting.

4. Comparison Testing

This section will show measurement results with several detector types and compare the performance of the PDTs and KM200 variant specific for these detectors. The following subsections will describe the detector under test and will illustrate the performance of the two amplifier types by showing the TIH and in some cases Rossi-Alpha distributions. Plateau counting characteristics will also be shown. Table 1 summarizes the results.

4.1. Detector number RS-P4-1612-102 (2” inch diameter 2 atm 3-He tube)

This is a very slow detector for which we increased the KM200’s shaper time constant to avoid severe double pulsing that is present when used with PDT amplifiers.
Figure 9 shows the plateau characteristics of PDT10A and KM200 after DPF adjustment. The KM200 has longer plateau than the PDT thanks to the double pulsing rejection filter.

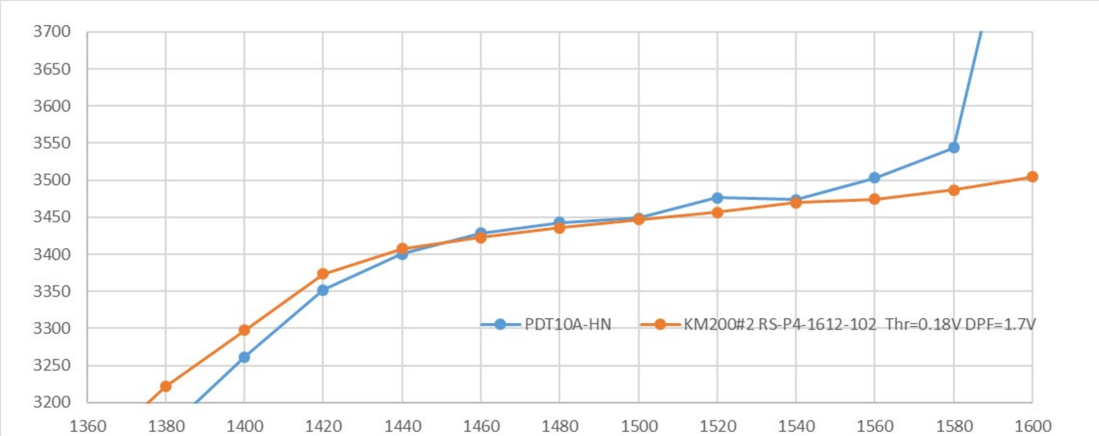


Figure 9. High voltage plateau of detector P4-1612-102.

The TIHs on the next figure demonstrates the effect of double pulsing. The peak at the beginning of the distribution on figure 10A will appear as false coincidences.

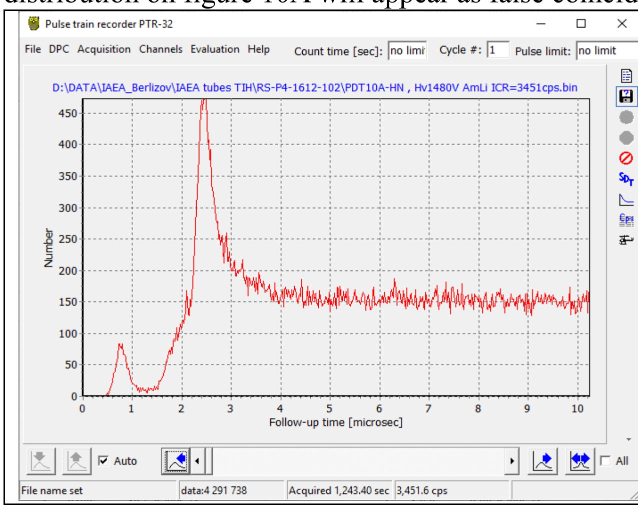


Figure 10A. Time interval histogram of PDT10A with detector RS-P4-1612-102.

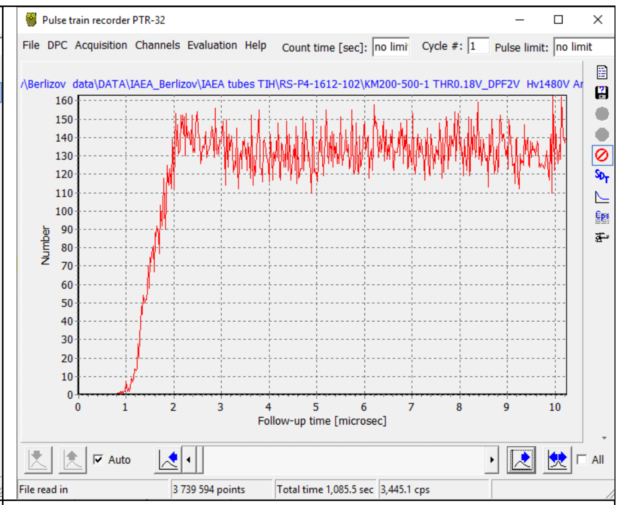


Figure 10B. Time interval histogram of optimized and adjusted KM200 with detector RS-P4-1612-102.

The dead time of KM200 in this case is about a factor of two less then PDT10A as shown on table 1.

Not all double pulsing events in the PDT are caused by detector pulse shapes. We observed some double pulsing instances that are due to internal pickup and insufficient threshold hysteresis. Figure 11 shows examples of the two double pulsing events.

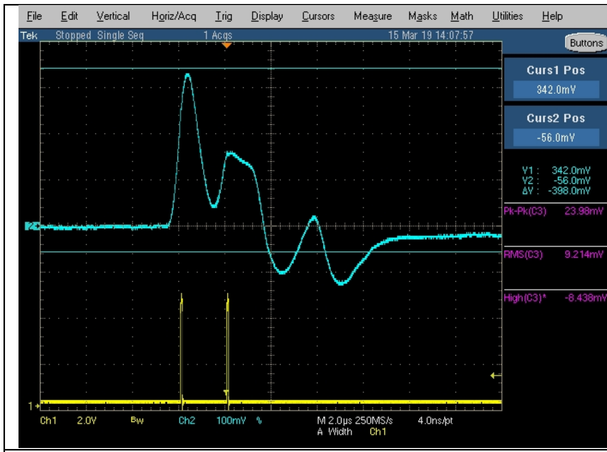


Figure 11A. Double pulsing due to detector pulse shape from the RS-P4-1612-102 detector connected to the PDT10A.

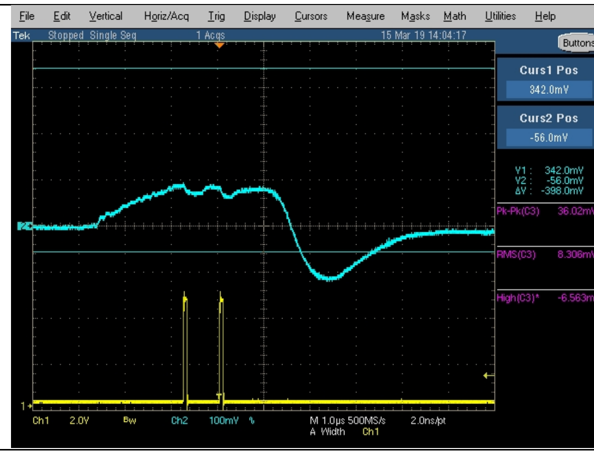


Figure 11B. Double pulsing due to internal pickup and insufficient hysteresis. As in the previous measurement the detector is RS-P4-1612-102 connected to the PDT10A.

4.2. Detector number RS-P4-0813-103 (1" inch diameter 4 atm 3-He tube)

This detector is about as fast as standard HLNCC tubes. The KM200 that is optimized for this detector is significantly faster and offers lower dead time than PDT10A
Figure 12 shows the plateau characteristics of PDT10A and KM200 after DPF adjustment.

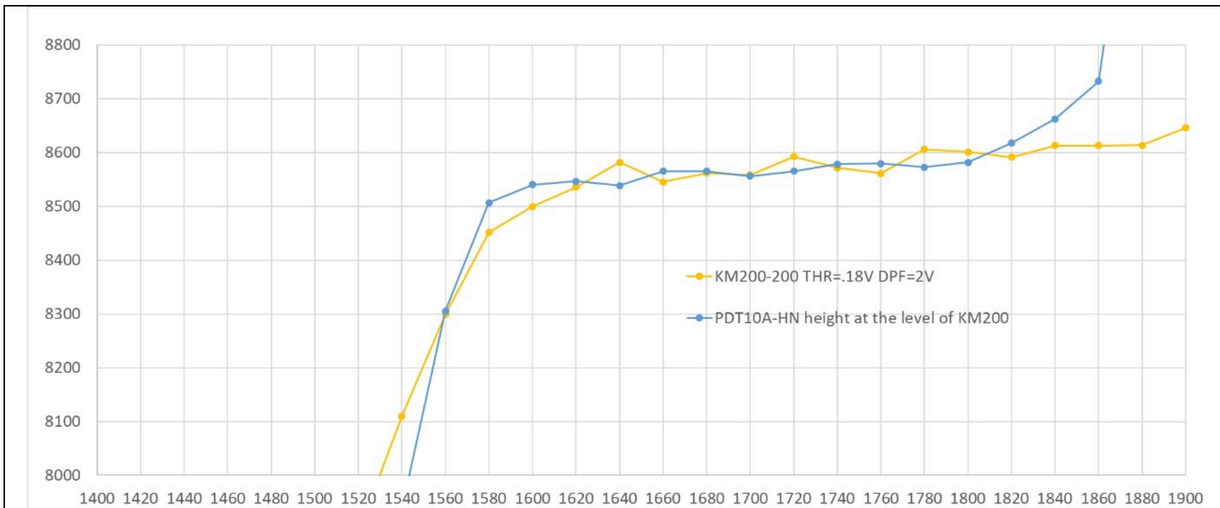


Figure 12. High voltage plateau of detector RS-P4-0813-103.

The TIHs on figure 13 show a significantly longer dead time with PDT10A. Also, there is an unexpected peak at the beginning of the PDT's distribution that looks like double pulsing. The source of this peak might be the internal signal pickup and insufficient hysteresis demonstrated on figure 11B

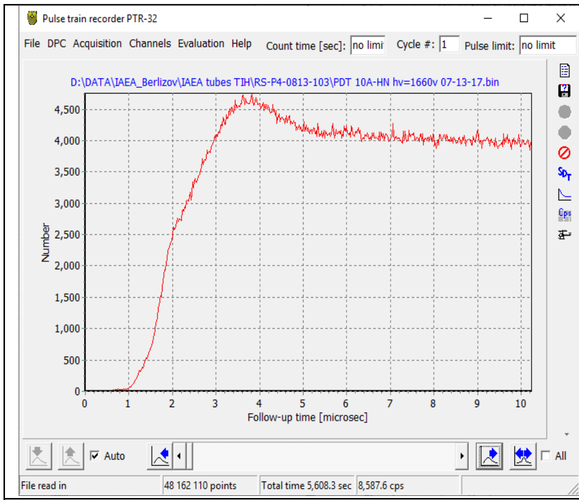
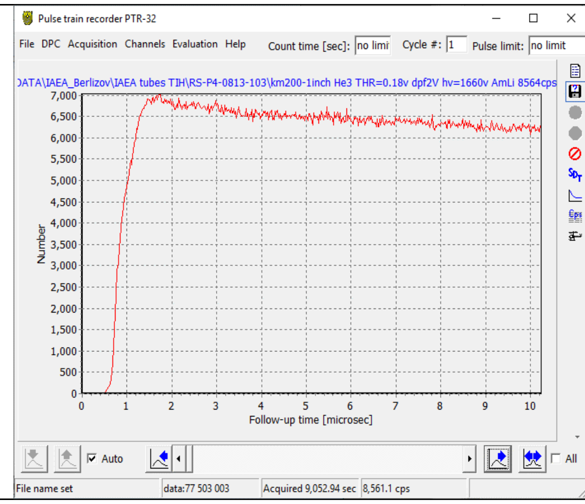
	

Figure 13. Time interval histogram of PDT10A with detector RS-P4-0813-103.	Figure 13. Time interval histogram of optimized and adjusted KM200 with detector RS-P4-0813-103.

4.3. Detector number RS-B1-0812-113 (1” inch diameter B10 tube)

This detector is a B10 tube that is faster than most 3-He detectors. PDT has provided a special fast amplifier (PDT10A-LP) that is intended for use with this detector and for fission chambers.
Figure 14 shows the plateau characteristics of PDT10A-LP and a KM200 optimized for this tube after DPF adjustment.

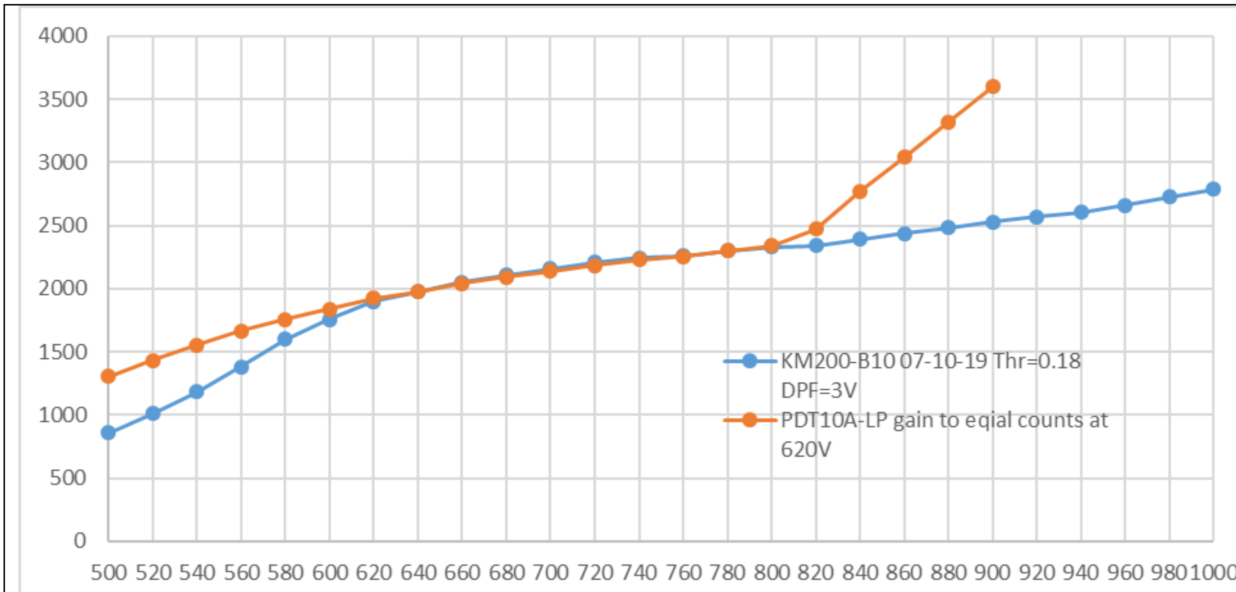


Figure 14. High voltage counting characteristic of detector RS-B1-0812-113.

Figure 15 shows the TIH distributions for the two amplifiers.

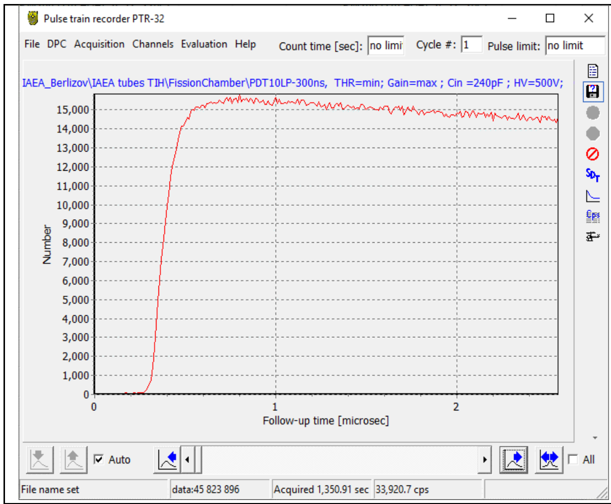
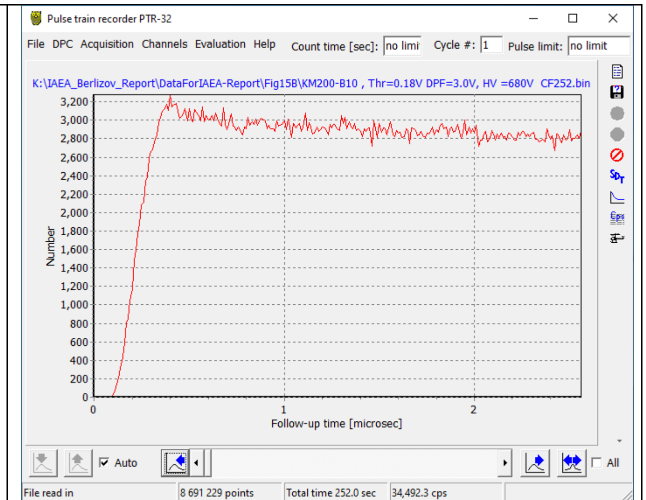
	

Figure 15A. Time interval histogram of PDT10A-LP with detector RS-B1-0812-113.	Figure 15B. Time interval histogram of optimized and adjusted KM200 with detector RS-B1-0812-113.

4.4. Detector number RS-P6-0810-102 (LANL fission chamber with added capacitance as substitute of IAEA CFLU01 fission chamber)

Even though the fission chamber is a very fast and gamma insensitive detector, its detection performance (counting efficiency, dead time, neutron/gamma rejection) depends on the front-end electronics. Realizing the full potential of the detector requires noise and speed optimization of the front end. In addition, the CFLU tube has very high output capacitance, which makes it difficult to achieve the optimal bandwidth and noise preamplifier performance. In our measurements we mimicked that by adding a 240pF to the output of the LANL FC detector.

Our optimized KM200 has a fast, low noise transistor at its input stage and thus we were able to achieve the low dead time and low enough noise for the minimum threshold to be below the detector's alpha background. In the comparison test the PDT threshold and gain were adjusted according to the recommendation of the vendor, PDT Inc. [4].

Figure 16 shows the TIH distributions for the two amplifiers. The KM200 fission chamber version is clearly faster than PDT10A-LP.

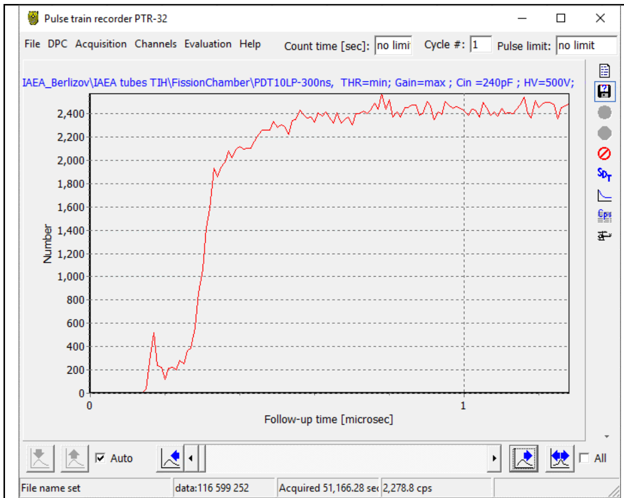


Figure 16A. Time interval histogram of PDT10A-LP with detector CFLU01.

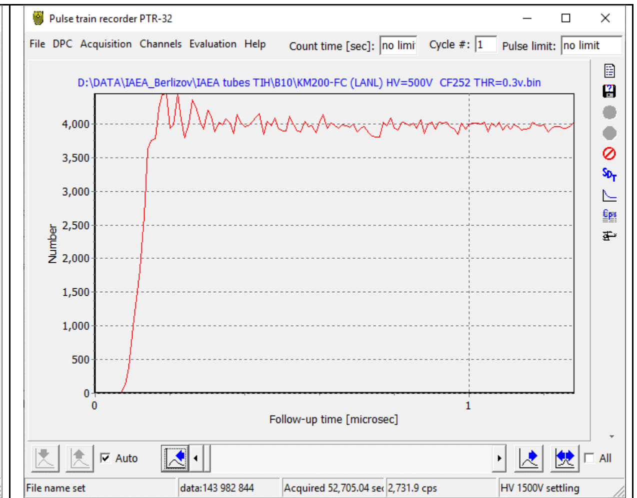


Figure 16B. Time interval histogram of optimized and adjusted KM200 with detector CFLU01.

The next figure shows Rossi-Alpha distribution for the same measurement. We included this figure to highlight an artefact of the PDT10A-LP. It seems like some pulses are lost up to 60us after the start of the distribution. Because of this behaviour, more data was taken using fast 3-He tubes to verify that it is a feature of the electronics and not the detector.

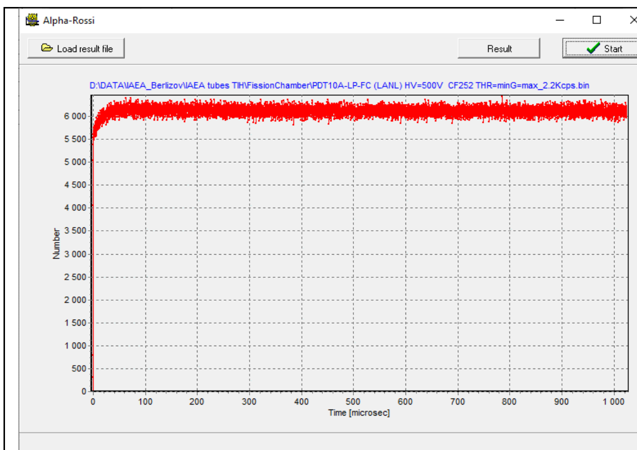


Figure 17A. Time interval histogram of PDT10A-LP with fission chamber.

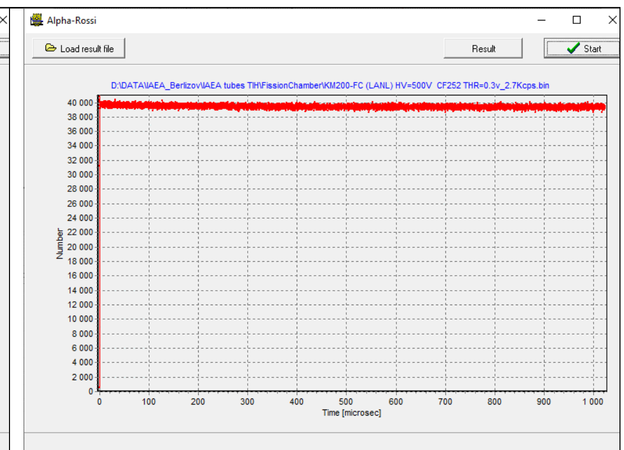


Figure 17B. Time interval histogram of optimized and adjusted KM200 with fission chamber.

4.5. Summary of dead time performance KM200s vs. PDT10A-HN and PDT10A-PL versions

		Count rate		KM200 Results			PDT Results			KM200/PDT	
IAEA Tubes	Tube Description	Measured [cps]	Normalized	Measured DT [us]	1/DT C.R. [cps*1e6]	Eff*CR	Measured DT [us]	1/DT C.R. [cps*1e6]	Eff*CR	Eff*CR Ratio	comment
RS-P4-1612-102	2" by 12 " 2 atm He-3 tube	18300	1.00	1.5	0.67	0.67	3.00	0.33	0.33	2.00	
RS-P4-0813-103	1" by 13" 4 atm He-3 tube	8550	0.47	1	1.00	0.47	3.00	0.33	0.16	3.00	PDT is not good match
RS-B1-0812-113	1" by 12 " B-10 lined tube	2200	0.12	0.25	4.00	0.48	0.40	2.50	0.30	1.60	
CFLU01	1" by 10 " U-235 FC 1 cps/nv	840	0.05	0.15	6.67	0.31	0.30	3.33	0.15	2.00	estimate from data sheet
LANL Tubes											
RS-P6-0810-102	1" by 10 " U-235 FC 0.14cps/nv	117	0.01	0.15	6.67	0.04					measured with 190uC Cf-252
RS-P4-0820-103	1" by 13 " 4 atm He-3 tube	7600	0.42	0.75	1.33	0.55					tube used in PMSC
RS-P4-0410-107	0.5" by 10 " 6 atm fast He-3 tube	4570	0.25	0.25	4.00	1.00					tube built by LANL specs

Table 1. Dead time evaluation with different detectors and electronics.

4.6. Temperature Stability of KM200

In the interest of full performance evaluation, we performed a temperature stability test of a KM200 amplifier optimized for B10 detectors. We expect similar stability for all KM200s. The B10 version stability was important because B10 detectors don’t operate at plateaus and temperature drift in the electronics’ gain or other parameters change the counting efficiency. Figure 18 shows the several plateaus in the temperature range +80C and -20C.

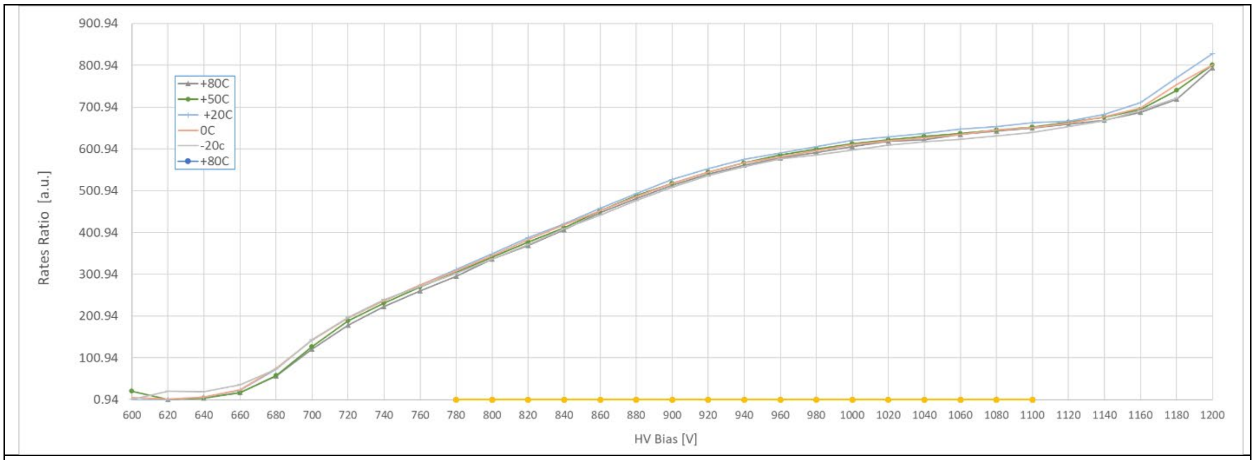


Fig. 18. Plateau characteristics taken in temperature range -20C to +80C

Figure 19 shows the relative change in count rate for different voltage in the range between -20C to +80C. The measured combined drift in 780V to 1100V operating voltage range is 0.04%/C without any compensation.

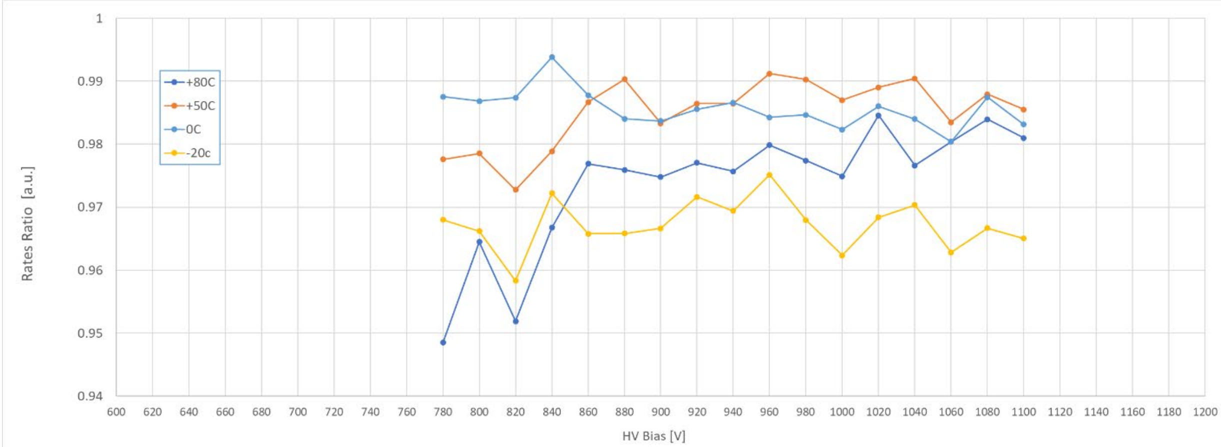


Fig. 19. Relative temperature change in temperature range -20C +80C calculated as a ratio to +20C plateau data.

5. References:

[1] Iliev, Metodi; Ianakiev, Kiril Dimitrov; Swinhoe, Martyn Thomas; "*KM200 Front-End Electronics for Thermal Neutron Detectors*", INMM 57th Annual Meeting; 2016-07-24 - 2016-07-28; Atlanta, Georgia, United States LA-UR-16-25182; 2016-07-22

[2] K. Ianakiev1, M. Swinhoe1, M. Iliev1, and N. Johnson2 “High Count Rate Thermal Neutron Detectors and Electronics” Proceeding of 2014 IAEA Safeguard Conference, paper CN–220–205

[5] Ianakiev, Kiril Dimitrov; Iliev, Metodi; Swinhoe, Martyn Thomas; Browne Michael, LaFleur Adrienne, US patent “High Rate Thermal Neutron Detectors and Electronics” September 24, 2019

[4] K. Ianakiev (LANL), Larry Eccleston, (PDT, Inc) Personal communication